On Z and Z + jet Production in Heavy Ion Collisions

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Abstract

Z+jet production in heavy ion collisions at the LHC is proposed as a possible probe of the properties of the dense hadronic matter. It is shown that the accuracy of this measurement with general purpose LHC detectors and under realistic experimental conditions can be high enough. It is argued also that Z-boson production and subsequent leptonic decay is a good reference process for this measurement, as well as for the QCD process of high P_T jet pair production.

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1 Introduction

The main physics motivation of heavy ion experiments at LHC is possible observation and study of the phase transition from the confined hadronic matter to the plasma of deconfined quarks and gluons (quark-gluon plasma, QGP). At the center of mass energies of few TeV per nucleon pair and for heavy nuclei $A \sim 200$, the energy density in central nucleus-nucleus collisions must be well above the expected phase transition value (see e.g. reviews [1, 2]).

Unfortunately, at present we know no single measurement that could give an unambiguous indication that the phase transition to QGP has taken place, so several observable effects should be measured in order to establish the existence of QGP and study its properties. A number of potentially measurable effects have been suggested and widely discussed in the literature (see e.g. refs. [2, 3]). A list of those taken from ref. [4], obviously not exhaustive and in no particular order, is shown below:

- 1. transverse energy distributions;
- 2. charged multiplicities;
- 3. transverse momentum distributions of identified particles;
- 4. strangeness production;
- 5. identical particle interferometry;
- 6. production of vector mesons with low and high mass;
- 7. continuum of lepton pairs;
- 8. continuum of direct photons;
- 9. high transverse momentum jets.

Detailed analysis of these topics goes far beyond the scope of this paper, but we would like to make some comments. Items 1 to 4 will certainly be sensitive to the final state effects, but it seems that reliable and unambiguous theoretical predictions about QGP manifestations are difficult to obtain [2]. Same is true for low invariant mass lepton pairs and light vector mesons, as well as for particle interferometry, with additional difficulties for the latter caused by very high precision of momentum measurements required. It also seems that the continuums of high invariant mass lepton pairs and direct photons will be very hard to study, mainly because of large irreducible backgrounds and low rates. Anyway, these two processes can be only considered as reference processes (see Sect. 3) as final state interaction should not significantly affect leptons and photons.

In fact, some recent investigations imply that direct probes of QGP should be hard enough in order to resolve sub-hadronic scales and distinguish confined and deconfined media [5]. So, one is essentially left with two topics most widely discussed in the context of QGP manifestations: heavy quarkonium production and high transverse momentum jets.

Yet again, the use of charmonium states $(J/\psi, \psi', ...)$ at LHC heavy ion experiments may be questionable, as their production rates even at average transverse momenta should be mostly dominated by weak decays of bottom hadrons, which take place far beyond the area where QGP can be formed. Υ family production at LHC looks more promising [6], especially when the peculiarities of the recent Tevatron data [7] are explained theoretically.

As for high transverse momentum jets,

$$p + p, A + A \rightarrow jet + X,$$
 (1)

their production mechanisms in hadron-hadron collisions are well understood in all accessible ranges of the initial energy and jet transverse momentum. It is believed that their properties should be affected by the dense hadronic matter [8, 9], resulting in measurable effects like additional energy loss and acoplanarity. Detailed investigation of high P_T jet production in heavy ion collisions at LHC and its comparison to that in pp interactions are well under way [4, 10, 11, 12]. Process (1) is especially interesting as jet quenching patterns are expected to be different for hadronic gas and QGP [8, 9].

We propose another hard process which also allows to investigate the effects of nuclear interaction on the propagation of a fast moving color charge, and can potentially distinguish the two states of the dense hadronic matter. This is the production of a leptonically decaying Z boson with high transverse momentum, in association with an energetic hadronic jet:

$$p + p$$
, $A + A \rightarrow Z(\rightarrow \mu^+\mu^-) + jet + X$. (2)

The detailed studies of the influence of the dense matter on jet development can be found in the literature (see e.g. refs. [2, 8, 9]). We do not consider them here; the purpose of this paper is just to show that such an investigation is theoretically interesting and experimentally feasible at the LHC heavy ion facility. As shown in Sect. 2, the cross section of this process is high enough and the background can be easily controlled using physically motivated cuts. For the purposes of QGP study, process (2) incorporates most of the useful features of (1), and offers some additional possibilities, which are also discussed in Section 2.

Another problem in heavy ion physics is that the cross sections here are not easy to normalize properly. This means that instead of comparing a distribution in nucleus-nucleus collisions with a similar one obtained in nucleon-nucleon interactions, one has to specify an appropriate reference process, and compare the ratios of two processes. In Sect. 3 we argue that Z boson inclusive production with a subsequent leptonic decay,

$$p + p, A + A \to Z(\to \mu^+ \mu^-) + X,$$
 (3)

is a good choice for the reference process, which satisfies all necessary criteria.

We have performed a Monte-Carlo simulation of the processes (2) and (3), assuming a realistic detector model, which can detect $Z \to \mu^+\mu^-$ decays and high P_T jets in the rapidity range |Y| < 2.5, for lead-lead collisions at LHC energies. Some results of our simulation and the discussion of various experimental aspects are presented in Sect. 4, and conclusions are drawn out in Sect. 5.

2 Z + jet production

At multi-TeV accelerators, high transverse energy jet production is expected to be completely dominated by the parton subprocess of (quasi)elastic gluon-gluon large angle scattering. Hence, in heavy ion collisions at the LHC one could investigate the propagation of gluon-initiated jets in the dense hadronic matter. The cross section of this process is relatively high and large statistics can be accumulated. QCD-motivated theoretical expectations are well tested at available energies and no serious discrepancies have been found. So, the process (1) is expected to be the major source of information about the effects of the dense matter on the fast-moving gluon fragmentation process in heavy ion collisions at the LHC. Possible changes in the energy loss mechanism in QGP as opposed to dense hadronic gas [8, 9] make this process even more interesting.

Nevertheless, some criticism should be expressed:

- As all participating partons in the initial hard scattering subprocess are gluons, it may be rather difficult to distinguish the effects of the initial state nuclear interactions like gluon shadowing from genuine final state dense matter effects. In order to do this, one has to know the gluon distribution functions in heavy nuclei at small fractional momenta, which would require tedious analyses of, say, charm and beauty production in lepton-nucleus collisions, and/or high P_T jet production in proton-nucleus interactions.
- No information can be extracted about the influence of the dense hadronic matter on the fragmentation of *quark*-initiated jets.
- Both jets in the event are equally affected by the dense hadronic matter. Most probably, the two jets are affected independently, which means that certain measurable effects like acoplanarity will be slightly reduced. But some possible coherent effects may escape detection.

Consider now the process (2) of a high P_T Z-boson production in association with a jet. In this case, relevant parton subprocesses are $q(\bar{q}) + g \to Z + q(\bar{q})$ and $q + \bar{q} \to Z + g$. Explicit calculations show that in the rapidity region |Y| < 2.5 and for both jet and Z transverse momenta exceeding 50 GeV/c, the relative contribution of these two parton subprocesses is $\approx 70 \%$ and $\approx 30 \%$, correspondingly. At least one of the initial partons is (almost certainly) a quark, and as far as quark distribution functions are readily measured in high energy lepton-nucleus collisions, initial state nuclear effects can be taken into account much easier and far more reliably than for the process (1). Moreover, in about 70% of events the detected jet takes its origin from a quark or an antiquark, and by choosing large |Y| values of the Z + jet system this proportion can be made even higher. This means that the process (2) gives a unique possibility to study the effects of the nuclear matter on a high purity sample of light-quark-induced jets 1 .

One could also speculate about tagging one of the $b(\bar{b})$ -quark induced jets in the processes p + p, $A + A \rightarrow b + \bar{b} + X$ and measuring changes in the $\bar{b}(b)$ -quark fragmentation process due to nuclear effects, but experimental feasibility of this study requires further investigation [13].

The process (2) has yet another advantage: the transverse momentum of the jet is highly correlated to that of the Z (in fact, neglecting the primordial P_T distribution of initial partons, in the absence of the initial-state radiation both P_T 's are exactly equal and opposite), so the jet in this case can be considered as tagged, and the effects of its further evolution should be easier to determine, as opposed to the two jet case, where both jets are affected by the final state effects.

From the experimental point of view, two high transverse momentum muons in (2) can be triggered with high efficiency and low background, using general purpose LHC detectors CMS and ATLAS. The muon trigger of these detectors provides μ detection with the P_T threshold of few GeV/c. Though it is optimized for nominal pp interactions, a similar muon trigger can be successfully used in heavy ion interactions as well. As for jet studies, jets with transverse energies above 50~GeV can be recognized with high efficiency and low background even in central Pb - Pb collisions [11].

3 Z production as a reference process

As mentioned above, serious normalization problems of the cross sections measured in heavy ion collisions can be avoided, if an appropriate reference process is found, and ratios of the two processes are compared in nucleus-nucleus and proton-proton interactions. It is most important that the reference process is not sensitive to final state nuclear interaction effects, so production of the large invariant mass lepton pair continuum seems to be an obvious candidate. Explicit calculation in realistic experimental conditions show, however, that a significant background coming from heavy quark semileptonic decays and low production rates of lepton pairs with high invariant mass $M(\mu^+\mu^-) > 100~GeV$ make this process almost useless for the above purpose.

We argue that the production of the Z boson and its subsequent leptonic decay $Z \to \mu^+\mu^-$ should be a good choice for a reference process for a number of reasons:

- Z decays weakly into muons, and final state interactions are clearly negligible in this case;
- the cross section is high enough, and the background can be shown to be well under control, so that the expected error can be made sufficiently small;
- the invariant mass of the produced system $\sqrt{\hat{s}} = M_Z$ is large enough, not too far from the average invariant mass of relevant high P_T jets, Z + jet system and other possible hard processes of interest, which makes their production kinematics quite similar;
- momenta of initial partons involved are large enough, $x_{1,2} \sim \sqrt{\hat{s}/s} \geq 0.02$, so that the very small x region, most strongly affected by the initial state nuclear interaction like gluon shadowing, is avoided.

- As the Z-boson is produced mainly by quark-antiquark fusion mechanism, a very good self-consistency check can be performed, by using quark and antiquark distribution functions extracted from deep inelastic lepton-nucleus scattering for describing Z inclusive distributions in heavy ion collisions.
- General purpose LHC detectors are capable of measuring Z production with high efficiency and resolution.

So, we propose to use the LHC heavy ion facility to study: i) the ratio of the number of high P_T jets to the number of detected $Z \to \mu^+\mu^-$ decays, and ii) the ratio of the number of Z + jet events to the same number of detected Z-boson decays, in various heavy ion collisions as well as in pp interaction. Note that for the latter process we expect significant cancellation of initial-state nuclear effects in the ratio, as initial quarks are involved in both the numerator and the denominator. Expected statistics will allow to measure the variation of these ratios with the transverse energy flow and other quantities of interest.

4 Experimental aspects and results of simulation

At LHC heavy ions will be accelerated up to the energies $E = E_p \cdot (2Z/A)$ per nucleon pair, where $E_p = 7 \ TeV$ is the proton beam energy for LHC. In the case of Pb nuclei the energy per nucleon pair will be 5.5 TeV and the design luminosity for a single experiment is about $L \approx 1.0 \times 10^{27} \ cm^{-2} s^{-1}$. The event rate for Pb - Pb interactions is expected to be in the range of $6 - 7 \ kHz$, but only 2 - 3 % of it will correspond to central collisions.

The rates of jet, Z+jet and Z production (processes (1-3)) in nucleus-nucleus collisions were obtained from pp interactions at the same energy using the linear A-dependence: $\sigma_{AA} = A^{2\alpha} \times \sigma_{pp}$, with $\alpha = 1.0$. The cross-sections in pp collisions were evaluated using the PYTHIA 5.7 Monte-Carlo program [14], with the default structure function set (CTEQ2L) and the K-factor equal to 2. The effects of deflection for quark structure functions with small fractional momenta in a nucleus relative to a free nucleon, and energy losses of high P_T partons in the dense matter were not taken into account.

The charged particle density in mid-rapidity range for the central Pb-Pb interactions at LHC is expected to be around 2000-4000. Several Monte-Carlo event generators have been created for simulating such collisions. HIJING [15], FRITIOF [16] and VENUS [17] are often used for nucleus-nucleus collision studies at SPS energies. We have used another approach to the simulation of this process, implemented in the SHAKER Monte-Carlo program, where gross features of soft particle production in heavy ion collisions are reproduced using some simple parametrizations. The main parameter for this generator is the charged particle density in central rapidity region, according to which the rates of various types of particles are computed. Particle production was generated according to the flat rapidity distribution in the region |Y| < 2.5 and experimental distributions measured at the Tevatron were used as transverse momentum spectra. After that, the

simulated central heavy-ion collision event was added to a hard pp interaction event with a high P_T jet and Z production. The following kinematical cuts have been applied:

- c.m.s. rapidity Y of the Z and the jet should be within the limits |Y| < 2.5;
- transverse momentum of each muon is larger than 20 GeV/c. Such muons will be measured with very high efficiency and low background [11];
- transverse energy of the jet is larger than 50 GeV. Reconstruction efficiency for jets with smaller transverse energy is fairly low, and large contamination from false jets is anticipated;
- transverse momentum of the muon pair is larger than 50 GeV/c. This cut eliminates the background from uncorrelated lepton pairs and maintains the balance of the transverse energy in the event.

In this kinematical region the contribution of parton subprocesses $q + g \rightarrow Z + q$ and $q + \bar{q} \rightarrow Z + g$ are 71% and 29% respectively. The Monte-Carlo study has shown that for $P_T > 50 \ GeV/c$ the jet recognition efficiency of 95% can be achieved, while the contribution of false jets can be reduced down to 10% [12].

The dominant background of $\mu^+\mu^-$ pairs in this case comes from two sources: Z production with the misrecognition of a fluctuation in the transverse momentum flow of soft particles as a jet, and QCD processes of heavy flavor pair $c\bar{c}$, $b\bar{b}$, $t\bar{t}$ production with their subsequent semileptonic decays. However, the cut upon the transverse momentum of the muon pair $P_T^{\mu^+\mu^-} > 50~GeV/c$ significantly reduces both of them, so that the final contribution of the background is less than 5% even without using the muon isolation criteria. The background due to uncorrelated muon pairs from π and K decays is negligible for $P_T^{\mu} > 20~GeV/c$. The expected number of jet + Z events is around 2000.

For the same kinematical region the expected number of high P_T jets in Pb - Pb collisions (process (1)) is $\sim 10^8$, while the expected number of detected $Z \to \mu^+\mu^-$ decays (process (3)) in the same reaction is around $\sim 5 \times 10^4$. The luminosity for lighter ions at LHC should be much larger, so that numbers of events in case of Ca - Ca interactions are expected to be about 100 times higher for the same period of running time, with similar background levels.

5 Conclusion

We have shown that the high transverse momentum Z-boson production in association with a hadronic jet in heavy ion interactions (reaction (2)) is a unique tool for investigating fast colour charge (mainly light quark) propagation through dense hadronic matter and searching for the manifestations of the quark-gluon plasma formation at high energy densities. Despite its smaller cross section, which still happens to be large enough to be measurable with sufficient accuracy using general purpose LHC detectors, the proposed

reaction can successfully complement similar studies of high transverse momentum jet production (reaction (1)) in a number of aspects, and has several important advantages.

In order to compare the rates of various hard processes in different heavy ion and proton-proton collisions, an appropriate reference process should be used. We argue that for a number of theoretical and experimental reasons, the process of Z boson production and its subsequent muonic decay (reaction (3)) is the best choice for such a process satisfying all necessary conditions.

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